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Research paper

Biogas infrastructures from farm to regional scale, prospects of biogas transport grids

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ABSTRACT

The volume of biogas produced in agricultural areas is expected to increase in coming years. An increasing number of local and regional initiatives show a growing interest in decentralized energy production, wherein biogas can play a role. Biogas transport from production sites to user, *i.e.* a CHP, boiler or an upgrading installation, induces a scale advantage and an efficiency increase. Therefore the exploration of the costs and energy use of biogas transport using a dedicated infrastructure is needed. A model was developed to describe a regional biogas grid that is used to collect biogas from several digesters and deliver it to a central point. The model minimizes transport costs per volumetric unit of biogas in a region. Results are presented for different digester scales, different sizes of the biomass source area and two types of grid lay-out: a star lay-out and a fishbone lay-out. The model shows that transport costs in a fishbone lay-out are less than 10 €ct m⁻³ for a digester scale of 100 m³ h⁻¹; for the star lay-out costs can go up to 45 €ct m⁻³. For 1800 m³ h⁻¹ digesters, these values are 4.0 €ct m⁻³ and 6.1 €ct m⁻³, respectively. The results indicate that cooperation between biogas producers in collecting biogas by means of a fishbone lay-out reduces the biogas transport costs relative to using a star lay-out. Merging smaller digesters into a smaller number of larger ones reduces the costs of biogas transport for the same biomass source area.

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1. Introduction

In the forecast of the Netherlands Environmental Assessment Agency (PBL), the volume of biogas to be generated in the Netherlands by digestion is predicted to increase by 74% from 8.6 PJ to 15 PJ in the time period 2010–2020; the total energy end use in 2010 was 2304 PJ, with 86 PJ from renewable sources. The main cause for the increase is the growth of co-digestion of manure and co-substrates. In the outlook for 2030 a further increase is foreseen to 61 PJ because of the ability to use biogas to produce heat at a high overall efficiency in a CHP and in the production of green gas [1]. The use of manure as a substrate is encouraged as it is one of the targets of the Sustainable Dairy Chain Initiative. The dairy sector organization, Nederlandse Zuivel Organisatie (NZO), wants the production of dairy products to be energy neutral. To reach this goal

manure fermentation plays an important role together with wind and solar energy [2,3]. The advantages of producing biogas could be a high climate benefit due to indirect emissions savings. The use of waste materials such as manure and biogas could contribute to a more diversified energy mix [4].

The roles in the energy market are changing. Traditionally the electricity and natural gas markets have been dominated by large-scale producers, traders and distributors. In addition to these large-scale firms, small-scale initiatives developed. In the Netherlands more than 400 local or regional initiatives encourage consumers to get involved in trade of electricity and gas and in energy production, mostly electricity. Local government, at municipal and provincial level, have adapted policies to reduce CO₂-emissions in line with the national targets. Often villages and cities even have a higher ambition, striving to an energy or CO₂ neutral community (*e.g.* [5,6] and several websites describe local initiatives [7]). In this new development biogas can play its role as a local source of energy. Biogas is less fluctuating and more controllable in comparison to solar and wind and can, to a certain extent, be used as balancing power [8].

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Nomenclature

CHP	combined heat and power
DH	district heating, a system for distributing heat generated by a CHP or boiler.
End user	the user of the biogas that is transported by the biogas grid; this can be an upgrading installation, a CHP or boiler.
GHG	greenhouse gas.
green gas	biogas upgraded to natural gas quality, also known as biomethane.
hub	a central place to collect biogas for further processing.
HHV	higher heating value.
NPV	net present value.
NZO	Nederlandse Zuivel Organisatie; NZO-Dutch Dairy Association.
PBL	Planbureau voor de Leefomgeving, Netherlands Environmental Assessment Agency.
SDE+	Stimulerend Duurzame Energieproductie, subsidy to encourage production of renewable energy. The subsidy SDE+ compensates producers for the unprofitable component in production costs and it opens in phases.
volume of (bio)gas	the volume of a gas is measured in m ³ at standard conditions (temperature 273.15 K, absolute pressure 0.101325 MPa).

If biogas is used to produce electricity in a CHP, the use of the produced heat needs to be considered. If the use of the heat from a CHP is not possible at the digester site, the biogas can be transported to a CHP elsewhere, close to a heat sink *e.g.* district heating (DH). The increase in overall energy efficiency can be as high as 50%, *i.e.* the thermal efficiency of a CHP [9]. In this way a renewable heat supply is established, whereby the costs of the heat depend on the transport costs of the biogas. Furthermore the SDE+ subsidy encourages the useful application of the heat from a CHP [10]. If regional plans for digesters are developed, the opportunity for cooperation arises. Apart from the improved heat-use, the collection of biogas from several digesters to a central location has more advantages: The installation using the biogas can be larger and generally produces at lower costs per unit because of economy of scale; *e.g.* if the biogas is used to produce green gas, large-scale upgrading and injection of biogas collected from several digesters could reduce costs [11]. In case of direct combustion of biogas in a CHP, not only a scale advantage on the investment is found, but also the electrical efficiency of a larger CHP is higher than the efficiency of a relatively smaller CHP [9]. Also, communal use of an installation like a storage-facility and flare, as safety measure, could partly justify an investment in a biogas grid. Shared use of biogas pipelines in a grid could reduce the costs of transport of biogas as compared to separate pipelines from individual digesters to the collection site.

Studies on biogas production and utilization comprise technical-economical, lifecycle and spatial evaluation of biogas plants and infrastructure *e.g.* [12–17]. Only few studies in the field of energy production from biomass by digestion address the use of an infrastructure for biogas collection and distribution. Börjesson, M. et al. chose a regional geographical level, incorporating local biogas systems and several energy demand systems, for the analysis of costs. The distribution of biogas between local biogas markets was studied, to investigate the requirements for policy support

to overcome techno-economic barriers of increased biogas utilization. The region considered was a county, consisting of four local government federations and 49 municipalities, with an area of 24,000 km². The final use of biogas in CHP generation in the DH sector was included. In addition to biogas transport by pipeline, distribution by truck of compressed biomethane was evaluated. They found that at lower subsidy levels an inter-municipal biogas pipeline is not cost effective and at a high subsidy level of 60 €/MWh large regional biogas grids are viable. The inter-municipal pipeline generally connects the rural area having a large biogas potential with an urban centre [4]. The study did not assess a biogas grid at a municipal level or the structure of a grid that is used to collect biogas from several farms at a regional level. The cost structure of the biogas transport was not presented in this study. Börjesson, P. et al. estimated the impact of a 55 km dual pipeline on GHG emissions. It was concluded that the energy use and the climate impact of building the pipeline are approximately 1% of the energy content and 1.2% of the emissions of the fossil fuel replaced [18]. The electricity needed for compression of biogas for transport in the grid was not specified. Hengeveld, E.J. et al. summarized the state of the art information on biogas grids and presented results of model calculations for a hub structure including several digesters on farms. These digesters are connected to the hub by means of individual pipelines. The total biomass source area ranges up to 313 km² that is the size of the source area in accordance with one very large farm scale digester. In the model the production chain of green gas was incorporated. It was concluded that, from a financial point of view, a large-scale centralized digester is favoured, while considering environmental aspects a biogas grid with a hub structure combining several smaller digesters may be better [11]. In a study on CO₂ abatement costs, Rehl T. et al. [19] included a system with transport of biogas in a 6 km dedicated biogas pipeline to a CHP. The abatement costs for a system with a 6 km biogas pipeline and a CHP with a functional output of heat and by-product of electricity showed to be negative. This indicates “an economic loss for society if the system would not be implemented” (Rehl T. 2013). The same system aiming at electricity production and by-product heat showed, depending on which reference was used for the heat replacement, a negative abatement too.

Many studies analysed the transport of natural gas. Generally the configuration studied has one or a few large-scale production units of natural gas. From these few sources the gas is transported by long distance high pressure pipelines and distributed to households and industry by a distribution grid (*e.g.* [20–23]). The main function of the pipelines is transport of gas, but also storage of gas in the pipeline, line-pack storage, is possible (*e.g.* [22]). In contrast, a biogas infrastructure may differ considerably from a natural gas infrastructure. The volume of biogas from a digester or from several digesters is much smaller than the volume of gas produced from a natural gas source. If the production of biogas is considered as a regional source of energy, the distances of transport are smaller for biogas compared to the distances involved in the transport of natural gas. Furthermore a biogas infrastructure may be needed to support the collection of biogas from several different small-scale producers to an end user *e.g.* if the biogas needs to be treated in a common upgrading facility or is used in DH. Two primary types of lay-out of a biogas collection grid can be distinguished. The first one allows for each individual digester to transport the biogas through a single individual pipeline to the end user. This grid type will be developed if biogas producers do not cooperate in the biogas transport. It is referred to as ‘star lay-out’, depicting its shape. In the other the biogas grid consists of pipeline segments. The biogas from several digesters is collected through relatively smaller pipelines, the ‘branches’, into a larger biogas

pipeline. This collecting biogas pipeline, the ‘backbone’, connects to the end user. The second grid type is referred to as a ‘fishbone lay-out’ [24,25]. To develop a grid with such a lay-out, cooperation among biogas producers is needed. For a high number of digesters and a large biomass resource area, the individual pipelines in a star lay-out are not efficiently used. So the costs of biogas transport will be higher than when using a grid with fishbone lay-out. In this study we use the star lay-out as a reference, to illustrate the financial advantage of the use of a fishbone lay-out. The biomass source region may exceed the source area for a farm scale digester.

Recapitulating, the use of biogas from digesters fed with a manure mixture is expected to increase, as is the demand for regionally produced renewable energy; this biogas needs to efficiently produce electricity and heat. Transport of biogas from a digester could contribute to cost reductions and an increase of energy efficiency. A biogas grid considerably differs from a natural gas grid. Therefore it is worthwhile to explore the costs and energy use of biogas transport using a dedicated infrastructure to collect biogas at a regional level. In this study the transport of biogas in a region using biogas pipelines, a biogas grid, is modelled. We did not consider the option to make use of trucks to transport compressed biogas [4]. Costs and energy use associated with transport of biogas in a grid are quantified. The study aims to make clear to what extent biogas collected into a dedicated regional biogas grid can contribute to a regional energy demand, e.g. the energy use in a village. The biogas could be used in a CHP or boiler in order to supply heat to households by DH.

In the next section the biogas grid model is presented. The model simulates the biogas transport in two lay-outs of a biogas grid that collects biogas from several digesters to a central collection point by pipelines. Differences between the collection of biogas with separate pipelines, the star lay-out, and a grid with shared use of pipelines, the fishbone lay-out, are shown. Results of the calculations are costs (€ct m⁻³) and energy use for transport (MJ m⁻³).

2. Methodology

2.1. The biogas transport model

For this study a model was developed to describe costs and energy use for a regional biogas grid. The flow chart in Fig. 1 illustrates the model design. The two variables in the model are the

size of a region (km²) and the average scale of digesters (m³ h⁻¹). For a given yearly biogas production per km² (m³ km⁻² a⁻¹) the two variables determine the average needed area per digester (km²), the number of digesters and the total biogas production (m³ h⁻¹) in the region. The volume of gas is measured in m³ at standard temperature and pressure. If large-scale digesters are implemented within the region being modelled, the digesters are spaced widely apart but the number of digesters is low; if small-scale digesters are used, they are closer to each other, and more digesters are involved.

Biogas production sites are connected to an end user by dedicated biogas pipelines, consisting of one or more pipeline segments. The lay-out of these pipeline segments, based on the chosen grid type, determines the length (km) of the pipeline segments in the grid, and the capacity of each pipeline segment (m³ h⁻¹). In a star lay-out the total length of the pipelines is larger than in a fishbone lay-out. In a fishbone lay-out the capacity in the backbone and in some parts of the branches will be higher than the capacity of a pipeline in the star lay-out. The pressure drop (MPa) in the pipelines depends on the capacity (m³ h⁻¹), length (km) and additionally the diameter (m) of the pipeline segments.

Finally the total costs (€) of the grid can be added together using an NPV calculation method. Investment costs for the pipelines are based on the length and diameter of the pipeline segments; operational and maintenance (O&M) costs (€a⁻¹) are added. Compressor costs consist of investment costs for the compressor, O&M costs and compression costs, i.e. costs for energy use of the compressor. The energy use (MJ a⁻¹) depends on the pressure needed to alleviate the pressure drop in the pipeline segments. The final results are presented as the costs and the energy-use per volumetric unit biogas i.e. in €ct m⁻³ and MJ m⁻³ respectively.

The choice of the diameter of the pipelines influences the costs and energy use. The choice for a small diameter pipeline segment keeps investment costs for the pipeline low, but causes the operational costs for compression to be relatively high. The compression costs can be lower if pipeline segments with large diameters, at higher costs, are used. The model optimizes the choice of pipeline diameter in order to minimize the costs of the biogas transport per m³. All calculations are based on steady state gas flow [21,27], and the absolute pressure in the biogas grid cannot exceed a specified maximum allowable pressure.

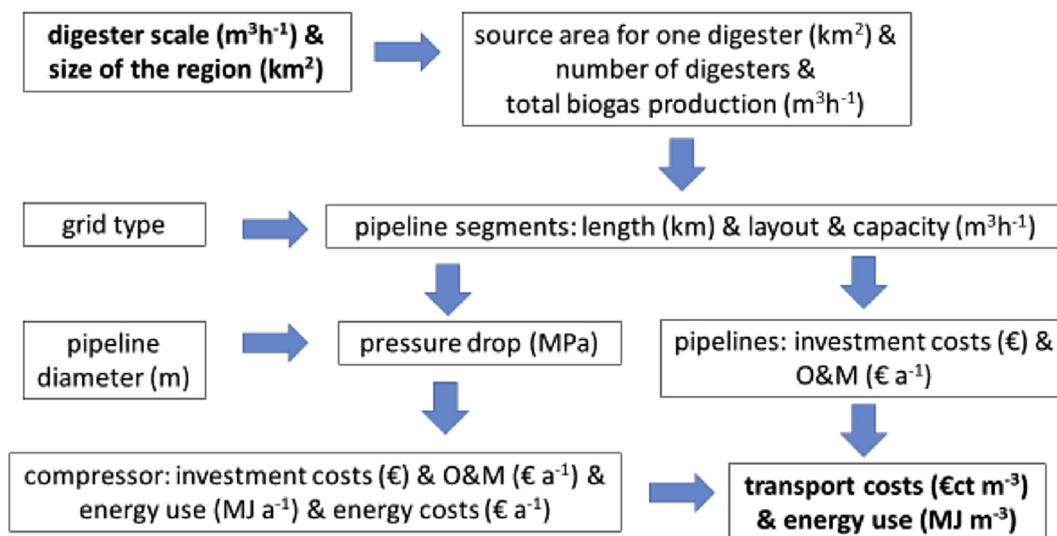


Fig. 1. Flow chart of the model calculations for biogas transport; the graph labels in the results section correspond to the words in bold.

2.2. The configurations and grid types in this study

The model is used for configurations of regions of different size; each configuration consists of digesters of the same scale and a grid to transport the biogas to the end user. The region and the area feeding into one digester are assumed to be square and in order to cover the region the digesters are equidistantly spaced within the region. The end user is at the centre of the region, labelled 'village'. As an example of a configuration, in Fig. 2 one hundred digesters and their squared source areas are depicted, in four quadrants. The number of digesters depends on the size of the region (km^2) and the digester scale ($\text{m}^3 \text{h}^{-1}$). In the model the smallest number of digesters in a configuration is four; in that case each quadrant has one digester. The next possibility has 16 digesters, four in each quadrant. So in the model the number of digesters needs to be an integer and is limited to certain integer values. This puts a restriction on the choice of the values of the two variables defined.

A biogas production model is used to evaluate the biogas to biomass ratio and in this manner the relationship between source area and digester scale is found. The biogas production model assumes co-digestion of manure (50%) and maize (50%), as weight percentages; 21% of the land to be arable and 25% of arable land to be used for growing energy crops. This results in an average biogas production of $52 \cdot 10^3 \text{ m}^3 \text{ km}^{-2} \text{ a}^{-1}$ [12].

The reference grid with a 'star lay-out' and the grid with a 'fishbone lay-out' are shown in Fig. 2. The star lay-out allows for each digester to transport biogas through a single pipeline straight to the end user at the village. At the digester site a compressor is installed to deliver the required pressure in the pipeline. In general, for the star lay-out, large digesters could require large diameter pipelines to transport the large volumes of biogas. If smaller digesters are simulated, the source area for one digester is smaller and the number of digesters for the same total area is larger. In that case more pipelines are needed for the region to transport the same total volume of biogas per hour to the village.

In the fishbone lay-out, see Fig. 2, the biogas from a quarter of

the region is collected into a main backbone. As compared to the star lay-out the total length of pipelines is smaller. At each digester site a compressor is installed to alleviate the pressure drop in the pipeline. Along the pipeline segments the pressure drop is cumulative and for each segment the pressure drop could be different depending on the length and diameter of the pipeline segment, the capacity of the segment and the absolute pressure in the segment [26]. The pipeline segment closest to the village has a large diameter allowing large volumes of biogas to pass. It is assumed that for two adjoining pipeline segments the diameter of the pipeline segment closer to the end user is equal or larger than the diameter of the other. It is assumed that at the end user the pipeline pressure is atmospheric *i.e.* 0.101325 MPa. The diameters of the pipeline segments are chosen such that the average transport costs of biogas for all digesters in a configuration are minimized.

2.3. The model calculations for transport of biogas

The assumptions and method to calculate costs and energy use for biogas transport in a pipeline are similar to those used in a previous study [11]. In a star lay-out, for each digester the length of the pipeline is calculated. In that pipeline the pressure drop is calculated using the five different pipeline diameters to select the diameters that satisfy the pressure requirement, with maximum pressure in the grid $< 0.9 \text{ MPa}$. For the remaining diameters the total costs (€ct m^{-3}) are computed *i.e.* investment costs, O&M costs of the pipelines and compressor and the costs for energy. Selection of the lowest costs for each digester and averaging the results for all digesters in the grid give the final (lowest average) transport costs (€ct m^{-3}).

For a fishbone lay-out a similar approach was used, although the number of possibilities can be much higher in larger grids because for each pipeline segment in the grid a choice of five diameters is to be made. In addition, the pressure drop calculation in a given pipeline segment also depends on the choices of the diameter in other pipeline segments, as explained above. The maximum

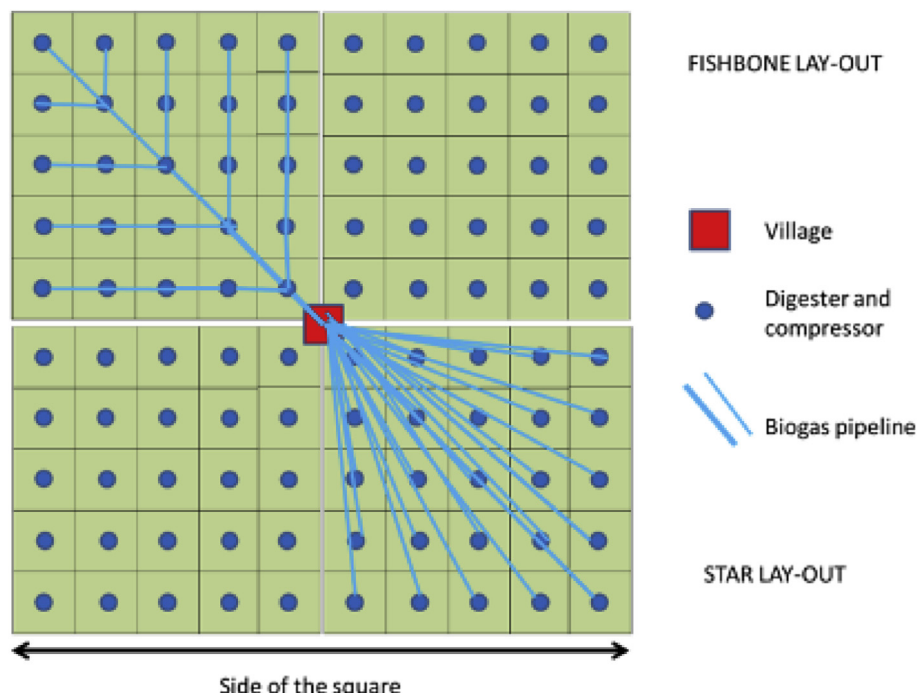


Fig. 2. Grid configurations with fishbone lay-out (upper left) and star lay-out (lower right); the distance between digesters depends on the scale of the digesters.

allowable pressure in the grid again is 0.9 MPa (absolute).

The choice of the diameter is a trade-off between the investment costs for the pipelines and the energy costs for compression. Large diameters of the pipeline segments cause high investment costs for the pipelines in the grid, but reduce the energy costs. While small diameters have lower investment costs, but require higher pressure for transport. Details of the model calculations and the used input data are given in the [Appendix A](#).

2.4. Safety measures

Biogas grids have some additional safety issues compared to natural gas grids. Overpressure as a result of sudden decrease in demand, toxic and corrosive properties of the biogas, and the unfamiliarity with biogas of external workers and the public. Safety measures are needed and available to counteract these risks, although there are some knowledge gaps on these aspects [24].

Included in the model are the following safety measures: Shuttle-valves to regulate the pressure at the joints of the pipeline segments in the fishbone lay-out; the cost of such a valve is estimated to be 20 k€. For each pipeline segment a shut-off valve (2.0 k€) is included for every 10 km. Flares (200 k€) are also required, with a capacity of 2000 m³ h⁻¹ each to meet the total biogas production in the grid in case of a sudden interruption of the demand (based on [24]).

It is assumed that H₂S and water are removed from the biogas before it enters the grid. Generally crude desulphurisation in situ by means of oxygen could give adequate results to reduce risks of toxicity and corrosion. The contamination level of H₂S in biogas is not regulated. In the Netherlands specification is still under development, but is set at 160 ppm [24].

3. Results and discussion

First the model results for costs of transport of biogas are presented (3.1), then the energy use by the compressors in the grid (3.2). These are followed by costs for safety measures (3.3). In section 3.4 a sensitivity analysis is included and finally a few related comments are given (3.5).

3.1. Costs of biogas transport

Model calculations were carried out for digester scales of multiples of 100 m³ h⁻¹ up to 1800 m³ h⁻¹, representing the range from very small to very large farm-sized digesters. Fig. 3 shows a selection of the results of the model calculations for a star lay-out; for clarity, not all results are presented. Costs are presented in €ct m⁻³; the graphs are presented up to a total square source area of 10,000 km², i.e. a side of 100 km. Looking at digesters with a scale of 300 m³ h⁻¹, the graph shows that in a square region with a side of 13.6 km, i.e. an area of 185 km², the minimal costs for transport of the biogas are 3.7 €ct m⁻³. This grid has 4 digesters, the smallest number of digesters in a grid. The square region with a side of 27.2 km has 16 digesters, and the minimal transport costs are 6.0 €ct m⁻³.

It can be seen that the transport costs in a grid are almost proportional to the side of the source area. This is mainly determined by the average length of the pipelines in the grid with a star lay-out, which is proportional to the side of the area. The small deviations from the straight line can be explained by the nonlinear increasing costs for compression for longer distances. At a certain level the choice for a pipeline with a larger diameter outweighs the increasing compression costs. For a large digester scale the pressure restriction on the pipeline also forces the choice of a larger diameter for the pipeline. As expected the costs to collect biogas from a

large number of small digesters are high. There is a clear scale advantage when using large digesters in the grid because less pipelines need to be laid in the same total source area and the costs of the pipeline with larger diameter are relatively lower than the costs of several smaller pipelines for the same total capacity. Furthermore, the costs of compression are also relatively low for pipelines with larger diameter. Note that in the figures the total amount of biomass and thereby the total volume of biogas produced is quadratic against the side of the total area; e.g. in an area with a side of the square of 25 km a total volume of 4 · 10³ m³ h⁻¹ biogas is produced, while in an area with a side of 50 km this is 16 · 10³ m³ h⁻¹.

In Fig. 4 a selection of the model results for the transport costs in the fishbone lay-out are presented. The increase in costs with the increase in distances of transport is more pronounced when the size of the area is under roughly 30 km and the scale of the digester is 100 m³ h⁻¹ or 300 m³ h⁻¹. This can be explained by the change in pipeline length used, in a similar way as in the star lay-out explained earlier. For these small scale digesters and an area size higher than 30 km the costs for the fishbone lay-out increase but at a slower pace. In this situation the advantage of using a collecting pipeline that reduces the pipeline length used, comes up; the diameter of the collecting pipeline in a fishbone lay-out is larger than the diameter of the individual pipelines in a star lay-out. The scale advantages for the transport of biogas when using larger digesters is present as well. The difference in costs for transport of biogas for the 900 m³ h⁻¹, 1200 m³ h⁻¹ and the 1800 m³ h⁻¹ digesters is relatively small as compared to differences in costs for the smaller scales of digester e.g. 100 m³ h⁻¹ and 300 m³ h⁻¹.

The graph in Fig. 4 shows that the size of the source area that can be served using a fishbone lay-out is limited; e.g. the model calculations show that the maximum of the side of the area in a fishbone lay-out with digesters producing 1800 m³ h⁻¹ biogas is 67 km when 16 digesters are in the grid, 4 in each quadrant. Adding more digesters of this scale, to a total of 36, results in a high flow of biogas in the pipeline segments close to the village, and consequently a high pressure drop in these pipeline segments. Even with the largest diameter of pipeline available in the model the maximum pressure restriction of 0.9 MPa cannot be met. For a star lay-out the distances within a grid obviously are limited as well, but they can be much larger.

As an example, a subdivision of the costs for a star and fishbone lay-out using digesters of scales 300 m³ h⁻¹ or 1200 m³ h⁻¹, is presented in Fig. 5. The region labelled I supplies the biomass used by 16 digesters with scale 300 m³ h⁻¹ or 4 digesters with scale 1200 m³ h⁻¹. Energy costs for compression are considered not to be a part of O&M costs. In the star lay-out the costs of pipelines and energy costs increase with an increase of the total biogas produced, i.e. with increasing source area. In the fishbone lay-out the increase in energy costs with increasing source area is more pronounced and the increase in pipeline costs is less pronounced than in the case of a star lay-out. Fig. 6 shows the choice of the diameters of the pipeline segments for the fishbone lay-out. The use of larger diameter pipeline segments in the collecting main depending on the size of the region is illustrated.

3.2. Energy use for transport of biogas

In Fig. 7 the direct energy, the operational electrical energy needed for compression, for the biogas in the grid is presented. The hatched areas comprise the bundles of lines that indicate the possible values for all digester scales from 100 m³ h⁻¹ to 1800 m³ h⁻¹. The energy use of the grids with a star lay-out and small digester scales is presented separately, as it was shown to be quite different. Generally the energy use for the star lay-out

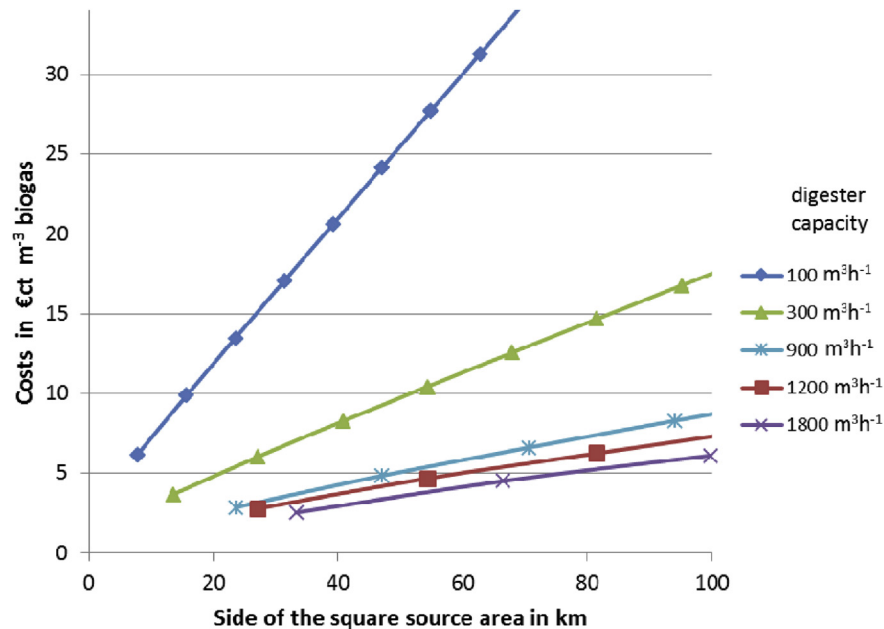


Fig. 3. Transport costs of a biogas grid (star lay-out), for different scales of the digesters; the side of the area (km) is used to represent the size of the region (km²).

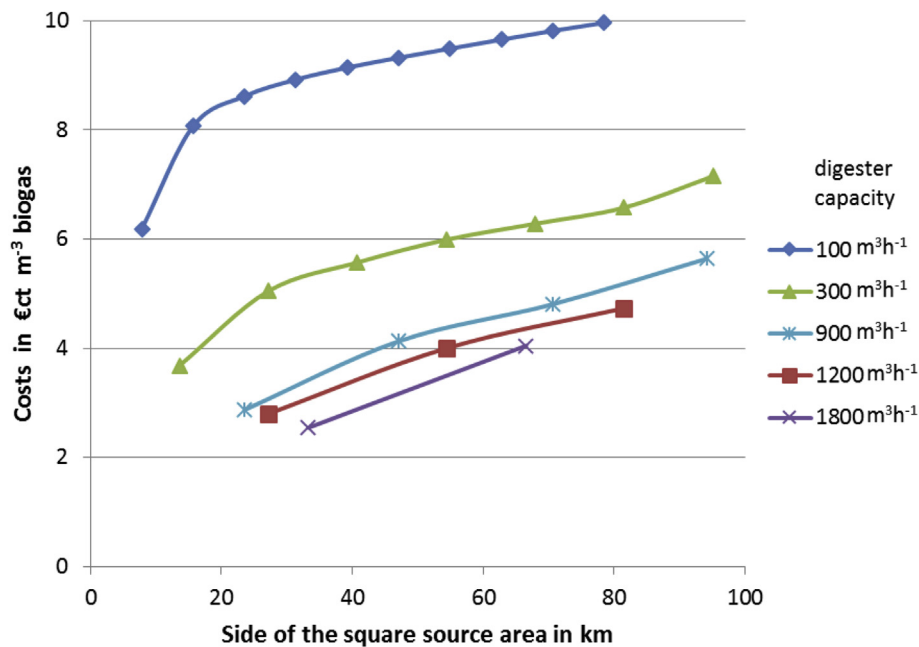


Fig. 4. Transport costs of a biogas grid (fishbone lay-out), for different scales of the digesters.

increases smoothly with the side of the source area, resembling the increase in required pressure for longer distances. The levelling off of the lines for a larger grid size is caused by the need for a larger diameter pipeline to economically transport the larger amounts of biogas. For a fishbone lay-out, the balance between using higher pressure or larger diameter pipeline is also present in grids in smaller regions. For a grid in a region with a side of the square area above 70 km, the energy use in a fishbone lay-out is higher than in a star lay-out. In this situation a higher pressure is needed to make the transport of the large total volume of biogas possible in the backbone of the fishbone lay-out; the largest diameters of the pipelines are in use. The grids with a fishbone lay-out show around

20% more energy use than grids with a star lay-out. The transport costs in a grid with star lay-out are higher than in a fishbone lay-out, as the difference in investments costs in the pipelines is higher as compared to the lower costs of energy use. For a grid with a side of less than 70 km the energy use in a fishbone lay-out is not always higher than in a star lay-out. The two separately presented lines in Fig. 7 show that the energy use in a grid with digesters of scale less than 200 m³ h⁻¹ in the star lay-out is much smaller than in a fishbone lay-out. Without considering these two lines, the ratio of energy use in a fishbone lay-out divided by the energy use in a star lay-out varies between 68% and 172% for corresponding regions and digester scales.

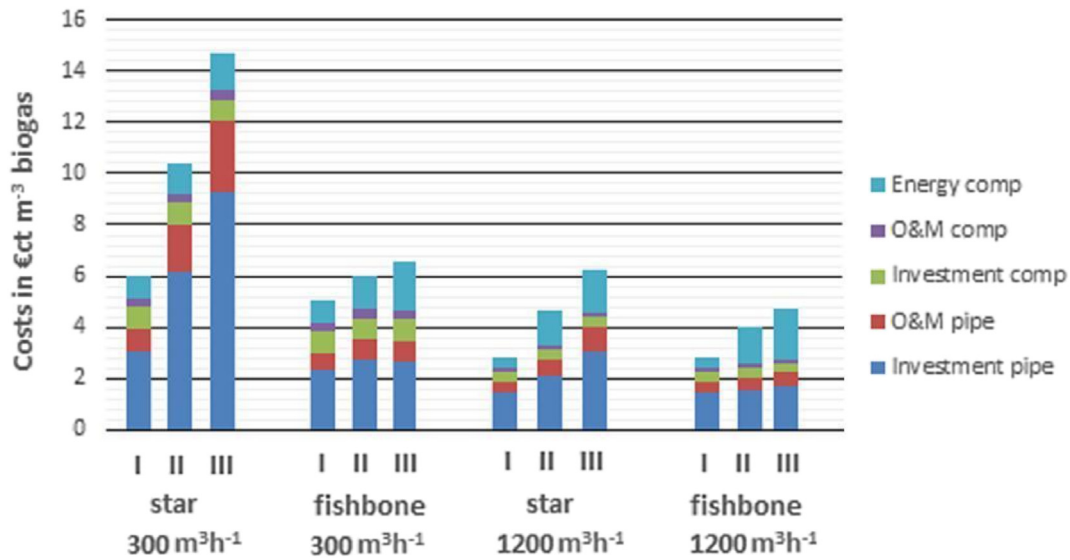


Fig. 5. Transport costs of a biogas grid; details for digester scale = 300 m³ h⁻¹ and 1200 m³ h⁻¹. The total biogas production of the biomass source region is labelled: I = 4800 m³ h⁻¹; II = 19,200 m³ h⁻¹; III = 43,200 m³ h⁻¹.

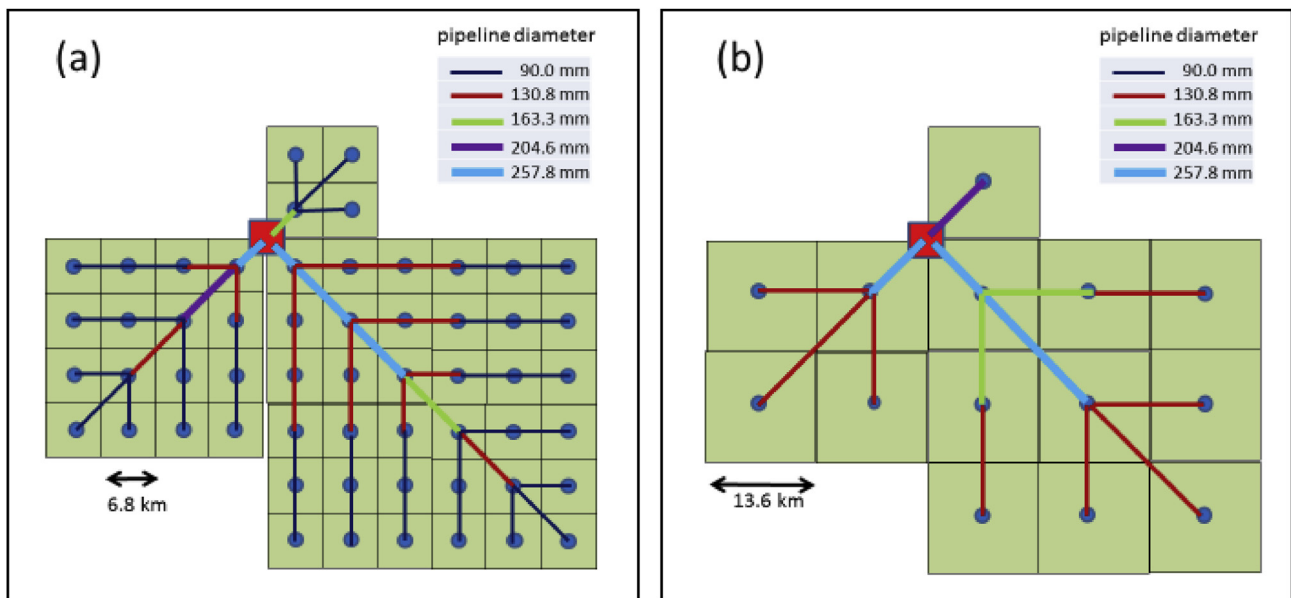


Fig. 6. Pipeline inside diameters in the fishbone grid; details for digester scale is 300 m³ h⁻¹ (a) and 1200 m³ h⁻¹ (b); only one quadrant for each region size is shown. The size of the biomass source regions correspondent to the regions in Fig. 5.

3.3. Safety

Table 1 shows results for the safety measures. Safety costs are dominated by the costs of flares. The safety costs showed to be more or less independent of the size of the biomass source region. Only for a small grid with a small digester scale the use of the flare with a capacity of 2000 m³ h⁻¹ leads to an overestimation of costs; therefore these are disregarded to find the values in the Table 1. For the small digester scale in a fishbone lay-out the costs for safety measures are slightly higher than the costs in a star lay-out. In a fishbone lay-out the shuttle valves add to the costs, while in a star lay-out the number of shut-off valves is higher.

3.4. Sensitivity analysis and additional scenario

The sensitivity to biogas and biomass yield (3.4.1), electricity

costs and the pipeline costs (3.4.2) is presented. Variation of other model parameters e.g. compressor costs; pressure requirement at the end-user; range of pipeline diameters; efficiencies used in the energy calculation, also leads to variation in biogas transport costs. In the last part transport of green gas instead of biogas is simulated in the case of decentralized upgrading biogas (3.4.3).

3.4.1. Variation in biomass yield and biogas yield

The biomass yield per km² in the biomass source area of the digesters influences the distance between the digesters. Therefore calculations have been done to find minimal biogas transport costs for different values of the biomass yield per km². In Table 2 the results are presented. A biomass yield of 100% corresponds with a biogas production of 52 · 10³ m³ km⁻² a⁻¹ and the associated transport costs are in Fig. 4. If the same digester scale is used, than the digesters are more widely spaced with decreasing biomass

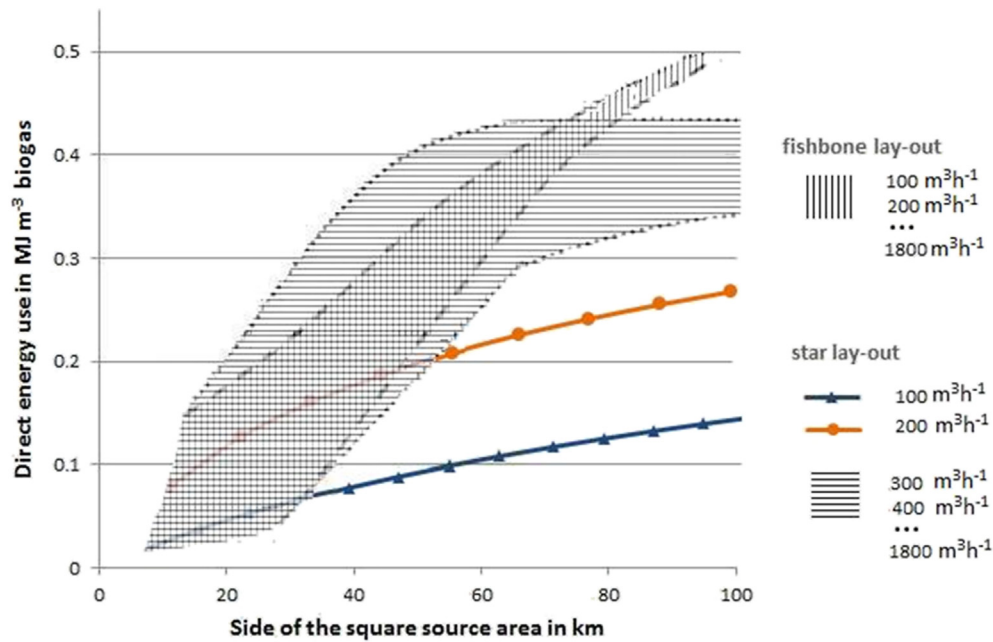


Fig. 7. Electrical energy use of a biogas grid for different scales of the digesters.

Table 1
Estimated costs for safety measures.

Digester scale in the grid ($\text{m}^3 \text{h}^{-1}$)	100 ^a	300	900	1200	1800
Star lay-out (€ct m^{-3})	0.35	0.3	0.26	0.26	0.25
Fishbone lay-out (€ct m^{-3})	0.6	0.35	0.27	0.27	0.25

^a The small grid with only four digesters of $100 \text{ m}^3 \text{h}^{-1}$ is disregarded.

yield, as a larger source area is needed to provide for the same total volume of biogas. In addition, the pipelines are longer, compression costs tend to increase or larger diameters of pipeline are used. Table 2 shows the increase in biogas transport cost [%] as a result of the lower biomass yield. In the comparison, the same total biogas production ($\text{m}^3 \text{h}^{-1}$) is assumed, i.e. the same number of digesters in a grid. The same results for variation in biogas transport are obtained if the biogas yield of the digesting process is varied. If the biogas yield for the digesters lowers, also the biogas yield per km^2 proportionally lowers.

3.4.2. Variation in electricity costs and pipeline costs

In a sensitivity analysis the pipeline costs and the costs of electricity are varied from -50% to $+50\%$ in steps of 10% from the used input values in the reference cases as shown in Fig. 5. In this section some results are presented.

If in the fishbone lay-out the costs of electricity are varied to 20% , positive or negative, the variation in transport costs is ca 5% in case of digester scale $300 \text{ m}^3 \text{h}^{-1}$, and ca 8% in case of digester scale $1200 \text{ m}^3 \text{h}^{-1}$. In a star lay-out the corresponding variation is ca 2.5%

and ca 5% . Variation of pipeline costs with 20% gives variation of ca 10% in the biogas transport costs in a fishbone lay-out and ca 15% in a star lay-out. The variation can largely be explained by the costs variation of electricity and pipeline combined with the cost structure for the biogas transport costs as presented in Fig. 5. For example, in a star lay-out the costs of pipeline have a larger share, therefore the variation as a result of pipeline costs is larger. In case of a biomass source area with production $4800 \text{ m}^3 \text{h}^{-1}$ and digester capacity $1200 \text{ m}^3 \text{h}^{-1}$, results are different; variation in electricity costs from -20% to $+20\%$ results in a variation of -5% to $+2\%$ in biogas transport costs; for the sensitivity to pipeline costs this is -14% to $+12\%$. The variation in electricity costs and pipeline costs shows to have a considerable impact on the choice of pipeline diameter in the optimization of the biogas transport costs using the model. In this case four digesters are connected to the hub by one pipeline only.

The variation in electricity costs and pipeline costs can cause a change in the choice of diameters of the pipeline; e.g. if the electricity costs increase the use of larger diameter pipeline is encouraged, as to reduce compression costs. In the star layout with

Table 2
Increase of biogas transport costs in a fishbone lay-out as a result of lower biomass yields or biogas yield compared to a biomass yield of 100% , i.e. a biogas production of $52 \cdot 10^3 \text{ m}^3 \text{km}^{-2} \text{a}^{-1}$.

Increase in biogas transport costs (%)		Digester scale ($\text{m}^3 \text{h}^{-1}$)				
		100	300	900	1200	1800
Biomass yield or biogas yield (%)	80	6–8	7–8	7–8	7–9	7–9
	60	16–18	17–20	18–21	18–20	16–23
	40	31–37	34–39	35–40	35–41	33–45
	20	66–78	71–98	74–78	72–77	68–89

digester scale $300 \text{ m}^3 \text{ h}^{-1}$, decrease of electricity costs or increase of pipeline costs could induce use of pipelines with smaller diameter; however in the sensitivity analysis the choice of diameters in the grid did not change. The grid already uses pipelines with small diameter, and no pipeline with smaller pipelines are available that can transport the biogas with the restriction of the maximum pressure. A similar result was identified, but to a lesser extent, in a grid with a fishbone lay-out. In a grid with star lay-out and digester scale $1200 \text{ m}^3 \text{ h}^{-1}$, the choice of diameters in the grid was different in almost all percentages used in the sensitivity analysis. As in such a grid are a lot of pipelines with different lengths and diameters, a change in pipeline costs or electricity costs makes one of them suboptimal, with a different choice as a result. In the grid with a fishbone lay-out digester capacity $1200 \text{ m}^3 \text{ h}^{-1}$ and a biomass source area with production $43,200 \text{ m}^3 \text{ h}^{-1}$ the variation does not introduce any change in the choice of diameter of the pipelines in the grid. This shows that the pressure needed for transport and the restriction imposed by the maximum pressure in the grid play their role in the large grid with relative large digester capacities. A similar result, although to a lesser extent, was found when a digester capacities of $300 \text{ m}^3 \text{ h}^{-1}$ are used with in a same sized biomass source area.

3.4.3. Decentralized upgrading of biogas

In the model, the biogas is assumed to be a mixture of methane (53.8%) and carbon dioxide (46.2%). As the final use of the biogas is for energy, the methane is considered to be useful, while the carbon dioxide is not. Avoidance of the transport of the carbon dioxide could reduce the transport costs [11]. Therefore we consider the case of decentralized upgrading of the biogas, i.e. removing (part) of the carbon dioxide before transporting the biogas in the grid. The upgraded biogas in this simulation resembles Dutch natural gas quality, L-gas (85.6% methane, 15.4% CO_2). Because the molar mass of carbon dioxide is higher than the molar mass of methane, the removal of carbon dioxide from the biogas reduces not only the volume, but also the density of the gas that needs to be transported, thus reducing transport costs. It can be shown that the costs for compression per m^3 do not depend on the density of the gas (e.g. [27]), but a lower density influences the behaviour of the gas in the pipeline inducing a lower pressure drop.

The minimal costs of a transport grid using upgraded biogas were calculated and compared with the minimal costs of the biogas which was not upgraded, to give the potential reduction in costs. Results show that in most cases the reduction in costs is between 0.5 €ct m^{-3} and 0.9 €ct m^{-3} . We found individual cases with a cost reduction up to 1.68 €ct m^{-3} . The costs of the upgrading itself is not included. Decentralized upgrading at the digester sites, in general, has higher costs per m^3 than at the hub, because of scale advantages. Feasibility of upgrading biogas before the transport could be assessed by comparing the costs of biogas transport first and then upgrading with the costs of upgrading first and then transport. An estimation of the scale advantage using an investment function for water wash [12] indicates the scale advantage to be larger than the reduction in transport costs. This suggests that “transport first and then upgrading” has lower costs. A green gas CHP has a higher efficiency than a CHP on biogas [9]. If the biogas is used in a CHP at a hub, the costs of biogas transport and use in a biogas CHP could be compared with the costs of upgrading, green gas transport and use in a green gas CHP. In a more detailed assessment also other aspects could play a role; e.g. the costs of transport of upgraded biogas may be lower than the model predicts, because of a higher input pressure of the biogas grid as result of the output pressure of the upgrading plant, depending on the upgrading method used.

3.5. Other comments

Although small biogas grids exist [11], the large-scale biogas grid is not an established technology. Pressures in the grid and the flow of the biogas in a fishbone lay-out are interdependent and the measurement and control of pressures in such a grid may need dedicated information and communication technology. Measurement is also needed for billing; at a minimum the quantity and quality of the biogas delivered by each producer need to be known [24]. Costs related to these aspects are not included in the model. We assume that the costs of biogas transport are shared by all producers, independent of the distance of the producer from the collecting point of the biogas. For a fishbone lay-out an allocation clause is necessary, because of the communal use of the pipeline system. Alternatively, in a star lay-out the exploitation of the individual biogas pipeline could be the responsibility of the one producer using the pipeline, which results in lower transport costs for the producers close to the village. The business model for a biogas grid is complex as many stakeholders are involved and long term high investments are needed, with financial risks that need to be assessed. The development of a biogas grid could start from an initiative for a relatively small grid that is extended by adding new producers of biogas later [28]. Klocke c.s. (2010) developed a business model for a regional biogas grid [25].

4. Conclusions – future research

A model was developed to describe the transport and storage of biogas by means of pipelines in a grid with two different lay-outs. The model shows that costs of biogas transport increase with increasing source area. In the star lay-out, transport costs are linear with the side of the square region. The costs of biogas transport in a fishbone lay-out are between 6.2 €ct m^{-3} and 10 €ct m^{-3} for a digester scale $100 \text{ m}^3 \text{ h}^{-1}$, depending on the grid size. In the star lay-out, the costs for the same sizes of grid range from 6.2 €ct m^{-3} to 45 €ct m^{-3} . For the $1800 \text{ m}^3 \text{ h}^{-1}$ digesters, the corresponding values are 2.5 €ct m^{-3} , 4.0 €ct m^{-3} , 2.5 €ct m^{-3} and 6.1 €ct m^{-3} . The model showed how cooperation of biogas producers in collecting biogas by means of a fishbone lay-out reduces the biogas transport costs relative to using the reference, a star lay-out. Merging smaller digesters into a smaller number of larger ones reduces the costs of biogas transport for the same biomass source area.

Energy use increases with the increase of the size of the grid. The use of a fishbone lay-out does not necessarily result in higher direct energy use as compared to a star lay-out. Often the choice of a larger diameter pipeline, to accommodate the larger amounts of biogas passing the pipeline, is financially preferred, rather than increasing the pressure in the grid. The electrical energy use is calculated to be in the range 0.1 MJ m^{-3} – 0.5 MJ m^{-3} , i.e. 0.5%–2.3% of the HHV of the biogas.

Whether the use of a dedicated biogas grid to transport biogas makes sense financially depends on the specific situation of the biogas use. To make biogas available in a village the transport costs add to the production costs of the biogas. In this case the transport of biogas makes it possible to produce renewable heat at the place where the heat is needed, e.g. by a CHP or boiler serving a DH. A more efficient use of biogas off-site could justify the transport of biogas. The costs of the increased efficiency in this situation are equivalent to the transport costs of the biogas in the grid; therefore the costs of transport of biogas can be used to find out whether the business case is viable.

Further research aims at the simulation of the use of line-pack storage in a biogas grid e.g. to supply flexibility in electricity production. When the share of intermittent renewable energy sources

increases, the proposition of biogas as a source of renewable energy suitable for balancing the electricity grid could be interesting. Possible advantages of using biogas as the energy source for the production and distribution of the biogas could be investigated. The alternatives for transport of biogas by pipeline, e.g. compressed biogas or liquefied biogas, could be assessed as well.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.biombioe.2016.01.005>.

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